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Biogenic waste methane emissions and methane optimization for bioelectricity in Nigeria

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ABSTRACT

Animal manure and municipal solid waste in atmospherically unconfined locations emit gaseous chemicals under the influence of some spontaneous reactions. These chemical substances, if allowed free escape into the atmosphere, can induce a global warming scenario with the potential for greenhouse gases (GHGs) to rise into the atmosphere. However, capturing these gases, especially methane, can be useful for bioenergy production and prevention of environmental pollution. This study tends to provide a theoretical estimate of methane emissions from both livestock manure in Nigeria and municipal solid waste deposits in some of the country's major cities. Ten-year data obtained from the United Nations Food and Agricultural Organization (FAO) was used to estimate the methane emissions from animal residues using a mathematical approach developed by the Intergovernmental Panel on Climate Change (IPCC). Emissions of methane from solid wastes were also estimated based on the 2011 cities' waste generation and management data from the Renewable Energy Department (RED) of the Federal Ministry of Environment, Abuja (Nigeria). In addition, methane capturing processes and optimization strategies were discussed as aids to any future prospects on the uses of methane for bioelectricity in the country. In addition, some identified factors militating against the accelerated progress for biogas production and utilization in the country is also highlighted. Results from this study indicated a large amount and increasing levels of methane emissions from animal residues and solid wastes. Capturing the methane emitted will not only mitigate against global warming but can also be a source of energy generation for the country.

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1. Introduction

Combustion of fossil fuels for urban and industrial energy needs has been a very common trend in the current global energy supply perception. More recent research efforts have pointed out that a higher percentage of world energy consumption has been obtained from fossil fuels over other conventional energy resources. Interestingly, Hamzeh et al. [1] buttressed that about 10% of the global energy supply is generated from biomass, while the remaining proportion is obtainable from fossil fuels and other conventional energy sources. This challenge of overexploitation of non-renewable energy resources has triggered the rapidity of research on bio-based materials for bioenergy application in recent times, as studied by [2,3] for biodiesel production using microalgae. Suberu et al. [4] also conducted a study on bioelectricity in Nigeria using a corn residue. In the broader picture, biomass for decentralized power generation has been a rapidly increasing idea in the power sector [5] of different countries. This directed effort of researchers seeks to avert the potential energy risk that awaits humanity regarding energy crisis and atmospheric pollution from energy use. Besides, overdependence on fossil fuels alone, which is undisputedly limited in quantity, may result in a surge of energy shortages in the near future. From this viewpoint, if the present scenario is allowed to continue for a longer period of time, all forms of modern development may be difficult to continue. This is the foremost reason that many countries, including international agencies at large, are working toward ensuring sustainable development. In achieving sustainable development, there must be an adequate transition to the emerging energy technologies [6] which are renewable.

RE development is not confined to any exclusive region. Global agitation for sustainable development advocates that both developed and developing countries entrench in RE exploitation. In industrialized nations, green energy generation is being accorded a greater priority, with swift and progressive development. Exploitation of biogas methane for energy consumption is rapidly progressing in nearly all developed countries. Basically, this can be attributed to a variety of productive factors supported by stern RE policy and implementation strategies. In advanced countries, regional agitations to either switch from a fossil regime to RE or to generate a reasonable proportion of the energy consumed from RE resources have been a front-burner issue for decades. A clear manifestation of such progressive thought is observed in the high growth rate of biogas power plant penetration in Germany from 1990 to 2008, as shown in Fig. 1 [7].

Furthermore, there are also some serious unfolding reports of global atmospheric pollution due to excessive burning of fossil energy sources. This has been noted in the form of emissions of harmful substances and the rise in global temperature resulting in the continuous depletion of ozone layers. An upward alteration in environmental temperature is scientifically known as global warming potential (GWP). These two major expected catastrophes (energy crisis and atmospheric pollution) have to be combated before they reach a climax. Environmental mitigation potential of bioenergy resources has been observed as one of the premeditated solutions as advocated globally on climatic hazards reduction measures [8]. Likewise, biogas has a very limited contribution to the greenhouse effect, depletion of the ozone layer and acid rain [9]. These characteristics, thus, make biogas a suitable RE source for sustainable development.

In 2006, India has a total installed capacity of about 125 GW of electric power, with 5% of it achieved through renewable energy (RE) resources [10]. Other developing countries like China, Thailand, Malaysia, Indonesia, Cambodia and Vietnam are currently recognized for their RE research progress, especially on biomass for energy. There are many rural and urban areas in developing countries whose inhabitants cannot afford to pay the high price of modern energy due to constricted economic rationale. Rural people, especially in developing countries, are usually low-income earners due to the predominance of self-employment. The development of RE systems in a rural district is thereby essential, as it is capable of enhancing the socio-economic standard of rural inhabitants. Besides, in urban settlements, particularly in the African sub-Sahara region, there is usually a high rate of unemployment and a limited potential for individuals to afford the cost of electricity. A shortage in the supply of electricity is a very common trend in the region due to poor generation mix. An RE system based on the available resources in urban and rural areas is a worthwhile approach to boosting the supply of energy.

Incontrovertibly, in the current global context of development, electricity cannot be discarded whenever development of any sort is on course. It is, however, well understood that energy demand heavily outweighs supply in developing countries with many small rural and remote communities. Connecting rural and semi-urban communities to a centralized power system imposes serious burdens on developing countries, which are subject to integrated constraints [5]. In such rural and remote communities, lack of proximity to the power system usually hinders the extension due to its high cost. The solution to this problem may be either the construction of additional transmission and distribution facilities or the provision of several standalone renewable electricity supply

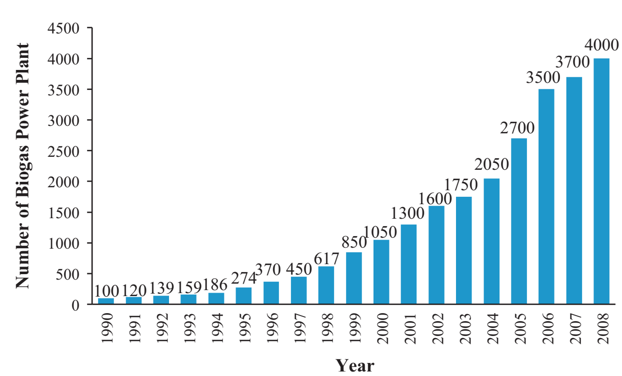

Fig. 1. Number of biogas power plant in Germany, 1990–2008.

systems. In this situation, biomass, which is widely present in such neighborhoods, can be considered as a viable preference to energy utilization; in addition, it can also be used to offset greenhouse gas (GHG) emissions. Therefore, the fundamental aim of this study is to explore the potential for spontaneous generation of biogas methane emissions from bio-waste materials in Nigeria. It also highlights some possible optimization approaches which could be explored as workable methods of biogas production to generate power in the country.

2. Methodology

2.1. Livestock production statistics

Livestock production in Nigeria and in the entire region of sub-Sahara Africa (SSA) is prominent and economically augmenting for the majority of peasant farmers. In the agricultural sector of the country, local economy revolves around livestock rearing, especially in the northern part of the country. Major livestock rearing in Nigeria—especially cattle, sheep and goats are predominantly owned by the Hausa–Fulani ethnic stock. The Hausa–Fulani accounted for more than 95% of pastoral herdsmen in the country. On a regional economic scale, in most of the dry zones in Africa, livestock occupy about 40% of the GDP [11,12]. Therefore, livestock wastes from cattle, goats, pigs, sheep and poultry are considered as potential feedstock in this study due to their availability and production quantity. Data from the United Nations Food and Agricultural Organization (FAO) on animal production for a period of 10 years (2001–2010) was explored. The analysis is conducted using the Intergovernmental Panel on Climate Change (IPCC) mathematical approach for the evaluation of methane emissions.

2.2. Municipal solid waste generation

Solid wastes are produced in both urban and rural settlements in every part of the world. Change in volume of waste generated from time to time depends on some factors like economic growth, human population and social standard of living. Millions in tonnes of solid wastes are generated annually in Nigeria. By limitation, this study focuses on the examination of waste generated in capital cities of the 36 states of the Nigerian federation and three other economically important cities. Data for the analysis was the result of a 2011 waste report compiled by the Renewable Energy Department of Federal Ministry of Environment, Abuja [13]. The original data were arranged in alphabetic order by city name, but for the sake of comprehensive analysis has been rearranged based on geo-political regional state capitals.

3. Sources of biogas methane production in Nigeria

Biogas is a combustible gas which is mainly produced by anaerobic digestion of biogenic waste materials. Biogas is primarily utilized for energetic applications such as heat production and power generation. Essentially, biogas is a collection of different gases, as presented in Table 1 [11,14], of which methane is the most important for energy purposes. There are various sources of biogas within the categories of biomass residues and waste. In the modern pursuit of optimization of energy resources for power generation, biogas can be considered one of the renewable energy resources that meet the criteria for power generation. In Europe [15–20] and some developing countries, especially China [21–24], biogas has been used successfully to generate heat and electricity in cogeneration facilities for consumers at distributed generation. This means that the process in which heat is generated within the power system setup is used for heat production while minimizing loss of heat to the surrounding. The application of biogas in power generation has largely been due to the potential production of the gas from variety of sources.

Table 1
Percentage chemical composition of biogas.

Gases	Volume fraction (%)
Methane [CH_4]	40–75
Carbon dioxide [CO_2]	25–40
Nitrogen [N]	0.5–2.5
Oxygen [O]	0.1–1
Hydrogen sulfide [H_2S]	0.1–0.5
Ammonia [NH_3]	0.1–0.5
Carbon monoxide [CO]	0–0.1
Dihydrogen [H_2]	1–3

Table 2
Livestock population in Nigeria from 2001 to 2010 [26].

Year	Cattle	Pigs	Goats	Sheep	Chickens
2001	15,133,400	5,249,540	45,260,400	28,692,600	124,620,000
2002	15,148,600	6,111,820	46,640,000	29,400,000	131,125,000
2003	15,163,700	5,677,900	47,551,700	30,086,400	137,680,000
2004	15,700,000	5,910,000	48,700,000	30,800,000	143,500,000
2005	15,875,300	6,141,220	49,959,000	31,547,900	150,700,000
2006	16,065,800	6,390,000	51,223,600	32,314,200	158,400,000
2007	16,152,700	6,642,340	52,488,200	33,080,300	166,127,000
2008	16,293,200	6,908,030	53,800,400	33,874,300	174,434,000
2009	16,435,000	7,184,360	55,145,400	34,687,300	183,156,000
2010	16,578,000	7,471,730	56,524,100	33,519,800	192,313,000

3.1. Animal manure

Animal production in Nigeria has a very long history starting from domestication of local species to commercialization of improved varieties. Presently, there are many commercial livestock-rearing centers on both private and government-owned farms, especially in the northern part of the country. Fulani herdsmen in the northern region usually own about 50–1000 cattle per family. Livestock rearing among them is distributed mainly across 80–90% of northern rural areas. On a commercial farm, especially in northern Nigeria, more than 1000 cattle can be found. Cattle rearing in the southern part of Nigeria is most common on commercial farms. The manure from these animals is one of the most suitable materials for biogas production through the process of anaerobic digestion [25]. Table 2 shows the livestock population in Nigeria from 2001 to 2010.

Major species of livestock in the country with the potential to produce a substantial quantity of manure are cattle, goats, sheep, pigs and chickens. Goat, sheep and cattle are predominantly reared in the north, while pig rearing is common in the south due to the predominant religious affiliation in the north being Muslim. Commercial chicken production predominates in the southern part of the country; meanwhile, the majority of urban and rural households in the country in general keep at least three poultry birds among other ruminant livestock. In terms of potential of biogas production in the country from animal manure, the northern part of the country can be considered to be more sustainable due to the physical size of the manure from cattle and their population by regional distribution.

3.1.1. Estimated biogas methane emissions from livestock manure in Nigeria

Methane emission from any form of waste can be a man-induced process. It can also be stimulated from spontaneous chemical reactions on waste in landfills or open sites. It is no doubt that a country like Nigeria produces a large quantity by volume of methane from animal dung and municipal solid waste (MSW) on daily basis. Biogas methane produced by this spontaneous reaction escapes freely into the environment and eventually increases the concentration of hazardous gases in the atmosphere. It was estimated that as much as 4% of global warming is due to methane emissions from waste [27,28]. Wastes generated from domestic animal rearing in Nigeria are usually dumped at waste dumping sites. In addition, sanitary wastes in landfills also cause emissions of methane [29] with an estimated 12% of the total global methane emissions released by the landfills [30].

As the global trend is advocating for a transition from fossil energy establishment to RE based on several socio-economic and environmental justifications, the necessity to embark on a process to capture biogas for energy production is inevitable. In this framework of thought, IPCC developed a mathematical approach [31] which is used for estimating the quantity of methane emissions as shown below:

$$\text{Methane } (CH_4) \text{ production from manure} = \sum_{(T)} \left[\frac{MEF_{(T)} \times N_{(T)}}{10^6} \right] \tag{1}$$

where

Methane (CH_4) production is measured in Gg/year
$MEF_{(T)}$ = methane emission factor based on livestock population, (kg/head/year or kg h^{-1} y^{-1}),
$N_{(T)}$ = number of heads of different livestock species in the country,
(T) = livestock category.

Methane production from livestock depends on the emission factors of animal management. However, emission factor selection can be influenced by regional climatic conditions [11]. In this work, the following emission factors in tropical African countries for pigs = 2, cattle = 1, goat = 0.22, sheep = 0.21 and chickens = 0.023 [11,32] were used. In reality, biogas methane production from animal manure does not depend on the population of the animal alone but also on the physical size of the manure produced. The quantity of the manure per animal as well as quality of feed consumption are other important factors. The result of the estimated methane emission from livestock manure in Nigeria based on the IPCC mathematical approach from 2001 to 2010 is shown in Fig. 2.

3.2. Municipal solid waste

MSW is a kind of waste generated from household activities, commercial center points, industrial manufacturing workshops and institutional places on a daily or periodic basis, depending on the schedule of activities. In simple terms, MSW is sometimes called solid waste. MSW consists of two principal fractions: biogenic and non-biogenic. Treatment of the biogenic component of solid wastes by anaerobic digestion produces biogas methane. Furthermore, in landfills, anaerobic digestion of organic waste releases methane and carbon dioxide, which escape into the atmosphere and pollute the environment [33]. In recent years, landfill areas have been major sources of biogas production. It was evaluated by [34] that 1 t of MSW deposited is capable of producing between 160 and 250 m^3 of biogas. Obviously, there is usually a percentage difference in the fractional biogenic and non-biogenic content of solid waste produced between an urban and a rural domain. This is primarily caused by the differences in the nature of activities between both places. In rural areas, agro-economic activities are predominant; therefore waste generated has a higher percentage of biogenic component than waste generated from urban districts. In developing countries, the separation of biogenic and non-biogenic components is not a well-organized process in the rural communities. They use manual techniques to separate these components, for instance using different waste bins for biogenic and non-biogenic waste. Using this practice, waste residues for feeding domestic biogas digesters can easily be sorted out. The other component of municipal solid waste which is inorganic (non-biogenic) constitutes the non-biodegradable inorganic substance, such as metal or non-biodegradable organic substances like plastic. The potential of biogas from MSW as calculated by [15] was in the range of approximately 88–138 m^3 based on 55% of methane yield, 44% CO_2 and 1% other gas components. MSW in Nigeria mostly contains biodegradable waste materials due to limited industrial activities in the country; they are characterized as follows:

- Household waste: These are waste products generated from various household activities. Mainly, they include vegetables, biodegradable kitchen wastes, textile rags, refuse papers, cardboards and household sweeping waste.
- Wastes from commercial focal points: Commercial centers including markets and other business places such as shopping malls generate this kind of waste. Nigeria is a developing country with many small and medium-scale commercial centers offering a variety of services. Waste generated in such places usually contain fruit wastes, vegetable wastes, unused plastic materials, packaging papers, cardboard papers, printed newspapers, waste rubber products, unused automobile tyres, slaughter waste, waste water, sewage sludge and sweeping refuse.
- Institutional and industrial wastes: Most waste products generated in institutional and industrial sectors of the country usually involve hospital waste, office sweeping waste, scrap metals, printed paper materials, chemical waste, food processing waste, packaging materials, agro-industrial processing waste, waste from timber processing industries and glass from ceramic industries.

Table 3 [13] shows the solid waste statistics in Nigeria by state capitals and major cities. The most widespread waste management practice in the country is that MSW is dumped in the street waste sites, dedicated open dumping sites or landfill areas. Designated dumping sites are limited to major urban cities and state capital cities in Nigeria. Due to the economic challenges of the country, human scavengers sometimes search for recyclable materials in the open dump areas to make a living. In Nigeria, waste collection in urban state capitals is adequately organized under the direct supervision of the State Ministry of Environment. Mechanical separation of MSW into biogenic and non-biogenic components in Nigeria is strictly limited to a few cities. However, in developed

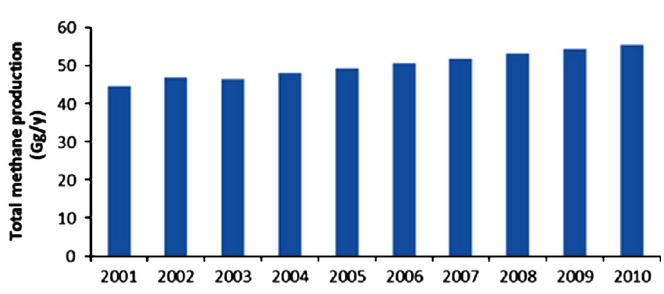

Fig. 2. Methane production from livestock in Nigeria from 2001 to 2010.

Table 3
Waste characterization in the Nigerian state capitals and some selected important cities [13].

Regional state capital	Cap/person/ day (kg)	Monthly waste (t)	Annual waste (t)	Organic waste (%)	Annual organic (t)
Northeast					
Bauchi	0.31	25,395	304,740	64	195,033.60
Gombe	0.275	14,006	168,072	70	117,650.40
Yola	0.28	25,365	304,380	68	206,978.40
Damaturu	0.242	14,001	168,012	70	117,608.40
Maiduguri	0.28	32,956	395,472	66	261,011.52
Jalingo	0.25	14,253	171,036	70	119,725.20
Northwest					
Kano	0.56	156,676	1,880,112	51	958,857.12
Kaduna	0.23	44,433	533,196	63	335,913.48
Katsina	0.32	18,452	221,424	70	154,996.80
Sokoto	0.281	15,255	183,060	66	120,819.60
Birnin Kebbi	0.28	15,456	185,472	70	129,830.40
Gusau	0.26	14,967	179,604	71	127,518.84
Dutse	0.3	16,340	196,080	70	137,256.00
Northcentral					
Lafia	0.21	13,956	167,472	70	117,230.40
Lokoja	0.26	15,478	185,736	70	130,015.20
Makurdi	0.28	32,956	395,472	66	261,011.52
Ilorin	0.25	34,560	414,720	70	290,304.00
Mina	0.246	14,989	179,868	68	122,310.24
Jos	0.23	27,667	332,004	57	189,242.28
Southeast					
Abakaliki	0.24	14,346	172,152	70	120,506.40
Umuahia	0.23	15,895	190,740	65	123,981.00
Enugu	0.31	16,009	192,108	58	111,422.64
Awka	0.31	25,395	304,740	60	182,844.00
Owerri	0.297	15,846	190,152	70	133,106.40
Southwest					
Lagos	0.73	255,556	3,066,672	36	1,104,001.92
Osogbo	0.24	14,957	179,484	60	107,690.40
Ado Ekiti	0.28	14,784	177,408	65	115,315.20
Ibadan	0.31	135,391	162,4692	61	991,062.12
Akure	0.32	15,089	181,068	60	108,640.80
Abeokuta	0.36	36,116	433,392	60	260,035.20
South–south					
Benin City	0.63	27,459	329,508	54	177,934.32
Yenagoa	0.23	14,246	170,952	65	111,118.80
Calabar	0.26	15,248	182,976	68	124,423.68
Port Harcourt	0.7	117,825	1,413,900	60	848,340.00
Asaba	0.28	15,950	191,400	60	114,840.00
Uyo	0.253	16,112	193,344	58	112,139.52
Other Cities					
Aba	0.31	64,347	772,164	70	540,514.80
Onitsha	0.7	84,137	1,009,644	62	625,979.28
Abuja	0.281	14,684	176208	65	114,535.20

countries, there is very high index of applying mechanical separation to recycle useful materials and biogas production from the biodegradable portion. Regardless of the separation mechanism, MSW application for electricity in a rural or urban area in a developing country is not a strange conception. In a country like Ghana, waste materials have been used for energy purposes under the direct supervision of the Renewable Energy Program (REP) of the Ministry of Mines and Energy, to run an internal combustion engine for electricity generation in some rural communities [5], such as a 12.5 kW biogas power plant in Appolonia [5,35].

3.2.1. *Estimated methane emission from MSW in major cities*

The presence of solid wastes anywhere emits methane either in open place or at landfill sites. Based on this study, methane emissions are calculated from the available data presented in Table 3 [13]. In view of the fact that only the biogenic (organic) fraction of municipal solid waste (OFMSW) has a potential contribution to biogas production, the calculation was based on the annual organic tonnage of the waste generated. Biogas density of 0.8 kg/m^3 [36] and 55% methane yield using the average value 160–250 m^3 of biogas produced from 1 t of MSW [34] is used for the evaluation. Figs. 3–9 show the results of the estimated methane emissions in Nigeria based on geo-political zones.

3.3. *Crop residues*

Application of crop residues for biogas production is not as progressive as that with animal residues and municipal solid wastes, though the availability of crop residues can offer substantial potential for bio-energy consumption via thermo-chemical conversion. Nigeria has poor technological background like other

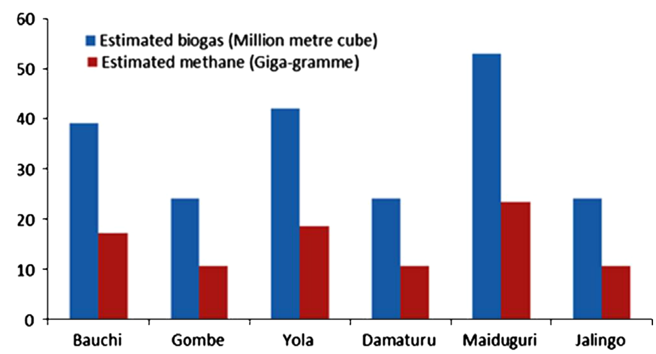

Fig. 3. Estimated methane emission in Northeastern regional state capitals.

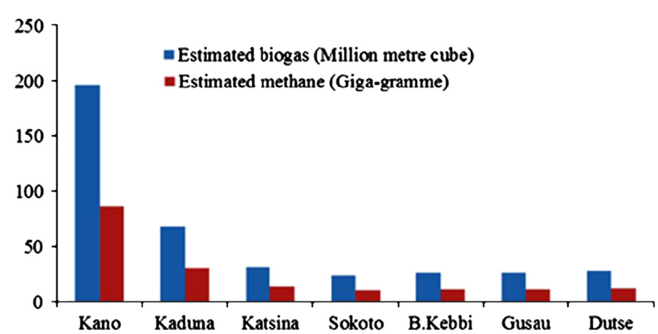

Fig. 4. Estimated methane emission in Northwestern regional state capitals.

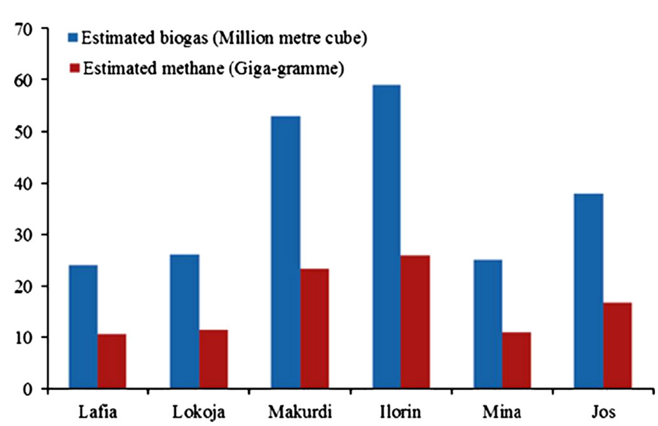

Fig. 5. Estimated methane emission in Northcentral regional state capitals.

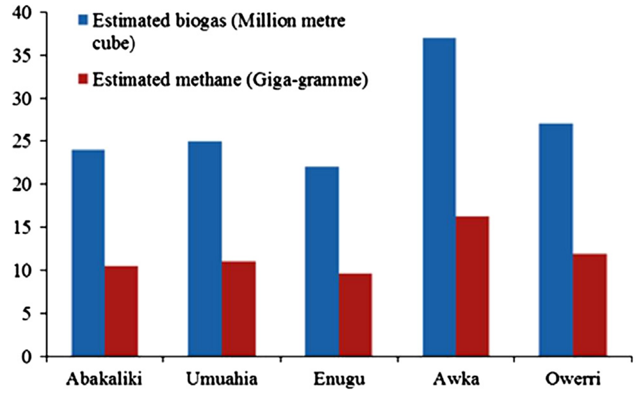

Fig. 6. Estimated methane emission in Southeastern regional state capitals.

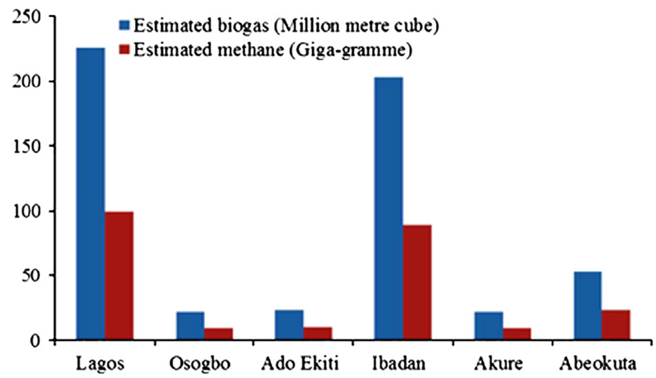

Fig. 7. Estimated methane emission in Southwestern regional state capitals.

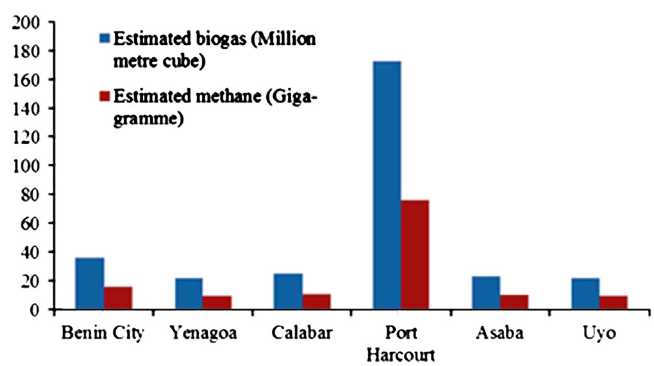

Fig. 8. Estimated methane emission in South–south regional state capitals.

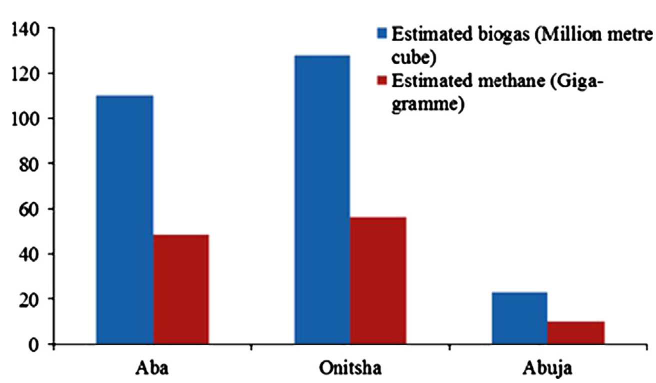

Fig. 9. Estimated methane emission in the selected important cities.

countries in the sub-Sahara Africa (SSA) region. This accounts for why the application of residues for power generation either by thermo-chemical or bio-chemical conversion has not attracted

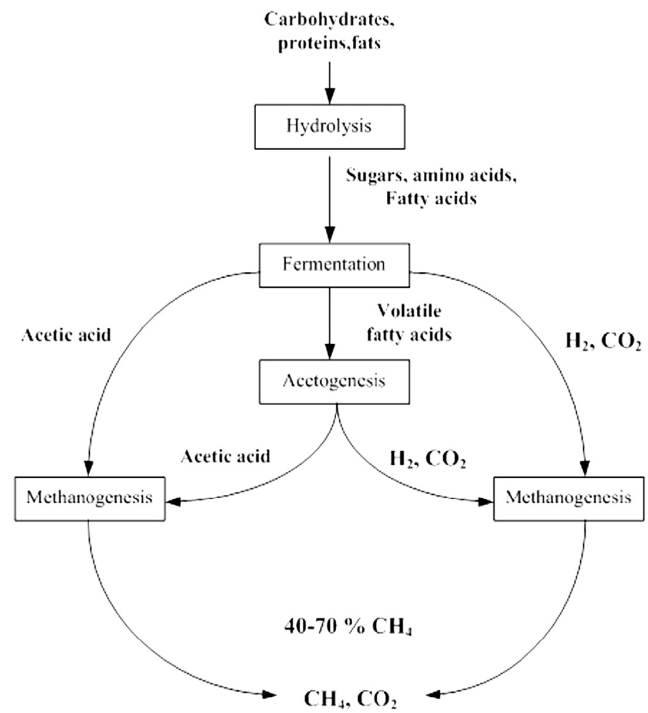

Fig. 10. Process flow of biogenic material through anaerobic digestion for methane production.

better consideration for energy production. Based on the frequency of biogas production statistics in the world, animal residues and municipal solid wastes are commonly used. Notwithstanding, it was reported by Isci and Demir [37] that cotton wastes are suitable for anaerobic digestion for biogas production, and El-Shinnawawi et al. [38] conducted studies on the uses of maize and rice residues for biogas. Several considerable bioenergy literature sources are currently focusing attention on the suitability of crop residues for biogas production.

4. An overview of biogas methane capturing technology

As mentioned earlier, biogas capturing technology from waste sources is by anaerobic digestion. It involves the biological action of bacteria to break down biogenic matter into biogas within a confined environment in the absence of air. The process is a complex and integrated bio-chemical reaction which is made up of four different stages in order of hydrolysis, acidogenesis, acetogenesis and methanogenesis [39]. A schematic of an anaerobic digestion process is shown in Fig. 10 [40].

The first stage of the biochemical process is hydrolysis. In this stage, enzymes reduce complex biogenic organic molecules of proteins, carbohydrates and other soluble compounds to simple soluble substances. The second stage is the fermentation process, which converts the products of hydrolysis—usually fatty and amino acids into volatile fatty acids (VFAs) under the influence of bacteria. The acetogenesis process occurs after fermentation with the formation of acetic acid, hydrogen and carbon dioxide. In the final stage of the biochemical reaction (methanogesnesis), methane and carbon dioxide are the chief components of biogas produced, but with a higher percentage of methane by proportion. Traces of other chemical substances like hydrogen sulfide, hydrogen, ammonia and nitrogen can be found in small quantities.

Anaerobic digestion of animal manure has been considered a very attractive treatment process with several benefits. Such

benefits include good quality of manure fertilizer produced due to less odor and pathogenic attraction, greenhouse gas emissions and biogas production [41–45]. Methane can be applied for energy purposes to replace fossil fuels and to reduce carbon dioxide emissions [45]. Biogas production from anaerobic digestion ushers in a new generation of revenue opportunity for farmers in the sales of animal manure. It is also possible to embark on self-generation of electricity consumed within farm centers. Waste-to-energy technology can be used to derive a socio-economic advantage from solid waste management in this modern time.

5. Technologies of power generation from biogas methane

Biogas is a clean and cheap combustible gas suitable for power and heat generation. The main gaseous component of biogas used for energy is bio-methane gas. It is an inflammable gas that burns easily with good heat-energy content. In a combined heat and power infrastructure usually referred to as cogeneration facility, effective optimization of biogas is possible with about 90% energy content of the methane fuel achieved with 30% and 60% heat and electricity, respectively [46]. Despite the high potential of biogas production, the number of biogas production facilities in Nigeria is less than 10, mostly serving prison yards and other basic institutions for cooking purposes. The reasons behind the slow pace of diffusion of biogas production and utilization in the country are highlighted in the next section. Fig. 11 shows the renewable power generation route from different biogas methane feedstock.

From a technological perspective, there are different electricity transformation plants which can make use of waste from animal manure or MSW for power generation. Technically, the process is generally classified into two kinds, which are thermo-chemical

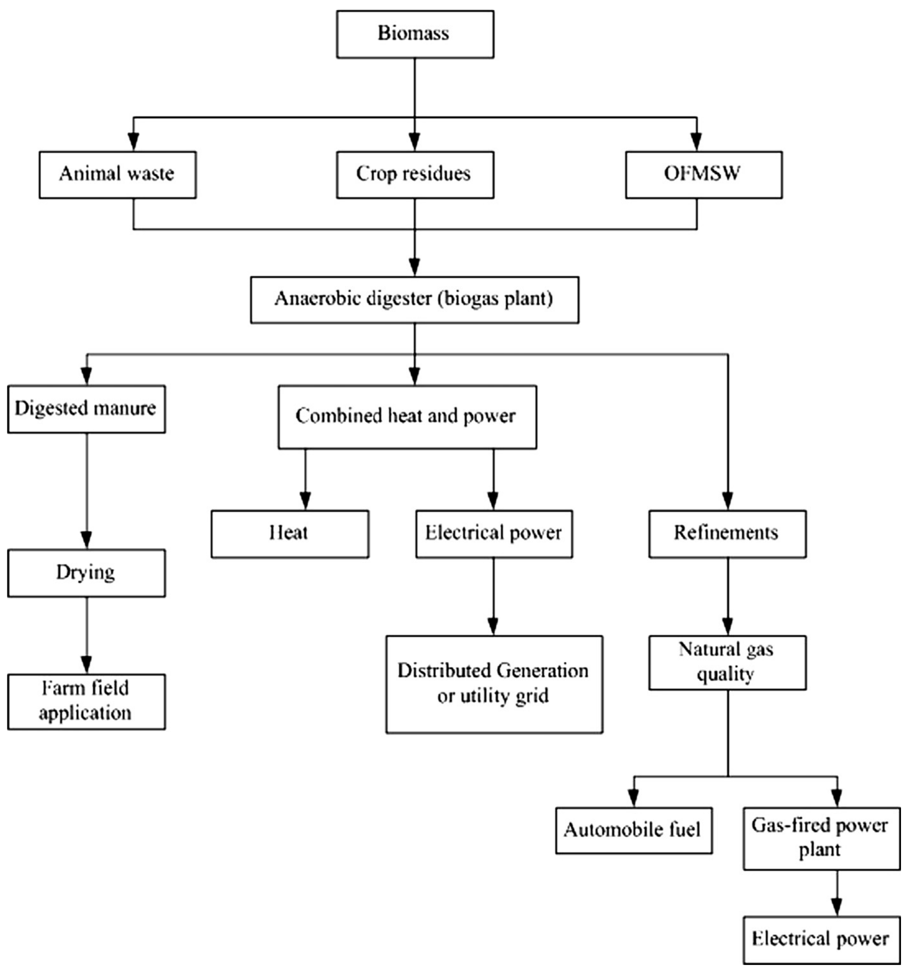

Fig. 11. Renewable energy routes from anaerobic digestion of different biogas feedstock.

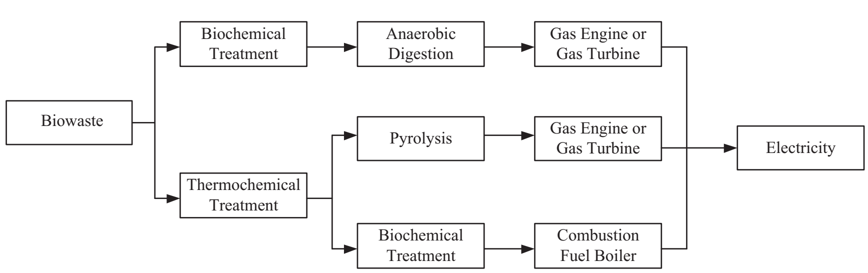

Fig. 12. Technique for power generation using MSW and animal waste manure.

and biochemical pathways. In the thermo-chemical route, high temperature is required for thermal degradation of the waste materials to release energy. Elementarily, a thermo-chemical process begins with combustion utilizing a sufficient amount of oxygen for the oxidation process. The thermal oxidation process facilitates the breakdown of the bio-waste material to release its stored energy. Pyrolysis and gasification are other thermo-chemical conversion processes involved in the production of combustible gas for power generation. On the other hand, biochemical handling of waste-to-energy (WTE) is mainly accomplished by anaerobic digestion. In anaerobic digestion, the intended end product is biogas methane, which can be applied for electricity generation using a gas engine/turbine or a combustion fuel boiler as illustrated in Fig. 12.

5.1. Factors responsible for the slow space of biogas development in Nigeria

Nigeria's electric power company is known as the Power Holding Company of Nigeria (PHCN). PHCN produces electricity from centralized generation infrastructures comprising thermal gas and hydropower plants. The power produced is conveyed via transmission networks with maximum and minimum voltage capacities of 330 kV and 132 kV, respectively. In 2007, it was acknowledged by the National Economic Empowerment and Development Strategy (NEEDS) that a national power demand potential of 10,000 MW is required for socio-economic transformation of the country [47]. Beyond 2007 to date, this potential of 10,000 MW is still the main target which is yet to be fulfilled by the government of Nigeria. The constraint of this unmet potential is largely due to widespread corruption and inadequate planning in the sector. The pursuit to increase the power supply to this desired capacity rely more on the use of natural gas for power generation. Indeed, this goes against the vista of clean development mechanism (CDM). Electricity generation in Nigeria is replete with backward tendencies such as shortage in energy production due to insufficient capacities. More to the point, the power industry in Nigeria is beleaguered by major intricacies in the core areas of operation: generation, transmission, distribution and marketing [48]. From the beginning, available power potential generated by the nation's power sector has not reached 5000 MW despite more than 8000 MW installed capacity.

Today, Nigeria is one of the major crude oil exporters in the world market. Unfortunately, the country depends largely on importation of refined petroleum products and their derivatives for domestic energy consumption. The government pays millions of US dollars to subsidize imported refined petrol-based fuels annually. Despite the continuous rise in electricity demands due to socio-economic development, increasing the output of electricity generated has not been forthcoming. About 80% of rural societies in Nigeria face the challenges of access to modern energy supply opportunity. This is due to poor rural electrification policy and constraints in procedures for implementation. In the past years, the Rural Electrification Agency of Nigeria (REAN) has been making efforts to electrify rural communities by connecting them to the national grid system. This is, however, not accompanied by a corresponding expansion of the potential for generation. This has obviously resulted in a technical failure of the projects. Statistics reveal that electricity efforts by the government and self-generation means by private individuals in rural communities of the country provide only 2% access to electricity in the country [49]. Besides, overall access to electricity in the country is rated as low as 46% [50]. In order to keep abreast of the modern trend for energy development, deployment of RE has become an option to the prevailing energy supply deficiency in the country. Apart from the general problems affecting RE development, the predisposition toward accelerated deployment of biogas in particular has been thwarted by the following factors.

5.1.1. Geographical location, socio-cultural and financial constraint

Renewable energy development (RED) is usually a target for rural and remote off-grid locations in developing countries. Nevertheless, urban centers, especially in developing countries, can also be marked locations due to perceptual cases of energy shortage in such countries. One of the major setbacks usually encountered is the sparse nature of rural settlements. This setback attracts a lot of high cost of capital investments for independent biogas development in several isolated communities. The limited economic potential of rural inhabitants coupled with socio-cultural restraint makes biogas development in rural Nigeria a slow option for energy utilization. The socio-cultural aspect of the problem is adjudged by the attitude of the government and potential stakeholders to foster the development of biogas for electricity production. In addition, poor understanding of the socio-economic benefits of biogas application for energy is a potential looming problem. This is basically due to the wide-ranging low level of education by the majority of people in the country. Lack of awareness has hampered mobilization for financial investment and support mechanisms. Mostly, poor institutional and government financial assistance for RED usually impede development. For this reason, there is a core hitch of undefined financial models and investment schemes for RED and consequently development of biogas.

5.1.2. Political consideration

Energy plays a vital role in local and international development. A fact remains that the cost of energy in the modern world can be directly related to the price of consumer goods and services. As the majority of countries in the world today practice democracy directly or indirectly, a political consent is considered inevitable in a quest for energy supply security. Currently, RE development of any sort in Nigeria has not been accorded a strong priority due to a weak socio-political ascent as related to weak policy.

5.1.3. Technical restriction and shortage of aided material

Inadequate technological background is another factor hindering progress on RE implementation. Technical expertise is required to effectively construct, install and maintain biogas digesters as well as to connect the digester to the power plant. A study by [51] revealed that in most developing countries, the majority of problems encountered with a low number of biogas digesters is very much associated with low technological know-how. Additionally, water is one of the aided materials used for anaerobic digestion. Generally, access to water in most parts of Nigeria is vastly restricted, as people heavily relied on flowing water from stream and rivers.

During the dry season, which generally covers a period from October to April, a shortage of water supply for any purpose is usually encountered. Provisional access to water by the government is highly insufficient to cater to domestic needs, not to mention other applications. This problem has forced thousands of people, especially in urban areas, to look toward self-provision of water by sinking private boreholes. This alternative is a capital-intensive project (with a cost of $3500), which can be afforded only by a few middle-income earners in the country. In rural areas of the country, dry seasons usually present unspeakable hardship to the greater part of the populace. For effective anaerobic digestion to occur, a sufficient amount of water is required to maintain a balance of chemical reactions. Therefore, this shortage of water can at a point in time create a technical malfunction of

the process and thereby hinder the continuous use of the biogas system for energy.

5.1.4. High cost of biogas power plant construction

In developing countries, development of biogas has also been hindered by the high cost of plant digesters, installation constraints and difficulty in acquiring spare parts [52]. As an approach to minimize cost, locally available materials have been used in China [53], concrete in Vietnam [54] and Pakistan [55]. Other low-cost materials have also been used in countries like Ethiopia, Tanzania, Bangladesh and Zimbabwe [56–58]. Also, due to the proven potential of biogas to substitute for kerosene, petrol, wood fuel and diesel, government and supporting organizations have recently facilitated rapid development of biogas in developing countries [59] using low-cost materials [55]. This has facilitated the development of millions of household biogas digesters in developing countries, especially a Chinese dome design type [60]. The integration of financial subsidies and the availability of traditional low-cost materials have been largely responsible for the increased number of biogas applications for heat and power. It is, however, regrettable that such organized effort has not been cultivated in Nigeria. Over the past few years, about 3.8 million digesters in India, 30 million in China, 60,000 in Bangladesh and a rising number in some African nations have been recorded [22,61–63]. Currently, the scenario in Nigeria is that there exists no well-organized financial incentive of any sort for RE development and hence biogas development for energy.

Therefore, the tendency toward biogas methane production and utilization in Nigeria for energy application depends on the following suggestions:

- Provision of bioenergy incentives to would-be biogas investors.
- Government support for distribution of biogas equipment to farmers at a subsidized rate.
- Development and implementation of a strong bioenergy promotion policy.
- Provision of technical training on the manufacturing of biogas equipment, installations and maintenance.
- Deployment of community-wide biogas digesters (centralized anaerobic digestion) for energy purposes.
- Adequate government intervention on the provision of aided materials like sustainable water services, polythene materials, concrete materials and effective feedstock transportation systems.

6. Toward biogas methane production optimization for power generation

6.1. Deployment and dissemination of biogas methane production technology

In a developing country like Nigeria, biomass feedstock use for biogas production can be enhanced to a realistic focus. In Nigeria, biogas production and utilization is a rather strange concept to more than 80% of the populace. To enhance its effective production and widespread adoption, there is a rigorous need for deployment of technology and proper orientation. Pragmatically, livestock husbandry farmers and waste management authorities in the country should be potential targets. Presently, the application of waste for energy is limited to sun-drying of livestock manure and direct burning for energy, which has been a common practice in northern Nigeria. Direct burning of animal manure has low energy efficiency. Undoubtedly, biogenic methane released during the drying process escapes freely into the atmosphere, which influences an unwholesome environmental situation. Free methane in the atmosphere has an estimated 23 times higher potential of global warming than does carbon dioxide [64]. In addition, ash release from the burning of animal waste in open airspace can obstruct human and animal respiratory systems.

6.2. Establishment of biogas CAD facility

Centralized anaerobic digestion (CAD) is a common phenomenon in the United States, Latin America, Europe and the Southeast Asian sub-continent, but Africa has very limited coverage and a small number of digesters. In areas where many feedstock materials are available for biogas production but are owned by individuals or organizations, there is a tendency to cooperate and feed a single biogas reactor to enhance the economics of production. The most common substrates used for CAD operation are manure and biogenic waste materials from industries [65], especially in industrialized countries. CAD can be implemented in both rural and urban areas, depending on the possibility of resolving associated integrated issues. Urban CAD systems sometimes use a central sewage system. In rural areas, CAD implementation is a somewhat difficult task; meanwhile, some techniques may be developed for centralized collection of potential waste feedstock. Moreover, the size of a CAD facility in a rural area is dictated by the availability of feedstock. Individual households in rural areas donate their biogenic waste for the centralized operation of CAD. At another level, CAD is more likely to be implemented in some closely related rural villages separated by a distance of few kilometers, say about 2–3 km. In rural areas of northern Nigeria without access roads, an animal transportation system is the preferable method; therefore, such a mechanism can be used to gather waste raw feedstock for CAD application. On the other hand, urban waste gathering in Nigeria is easy because of an organized transport arrangement under the Ministry of Environment for each state of the federation.

Furthermore, there exists an advantage of co-digestion in a CAD digester facility. In a co-digestion operational scheme, different substrates are brought together as feedstock under one large anaerobic digestion facility to directly maximize biogas production output. Co-digestion is used to enhance bioconversion rate and methane yield capacity [66]. It is also a bio-waste treatment method where different wastes are mixed and treated together [67] while increasing digestion rate as well as stabilizing the reaction [68]. In the modern power industry, there is an emerging technology of modular bio-power plants to complement power generation using biogas from a CAD facility, especially in remote areas. The new power plant can be designed such that it can be calibrated in line with the power demand of the community or based on the biogas potential supply [69].

6.3. Refinement of biogas quality for diverse energy use

A possibility exists for the application of biogas methane as fuel in energy-consuming systems other than the traditional Combined Heat and Power (CHP) system. The essence of reusing the heat produced in the CHP system is to minimize heat loss to the surroundings. Heat freely released into the environment has a potential impact on increasing the environmental temperature with the attendant effects on biodiversity. There are two basic ways of refining the biogas, either slight engine modification or refinement of biogas methane fuel to a natural gas quality. Biogas usually contains a higher percentage of methane compared to other component gases. For example, it was reported by Appels et al. [70] that anaerobic digestion of biogas contains about 55 to 65% methane and 30 to 40% carbon dioxide. Moreover, refinement of biogas to attain the quality of natural gas simply means removing impurities such as carbon dioxide, hydrogen sulfide

and others to obtain a very rich methane gas. This process ensures that more than 90% methane purity is achieved, which can be used for diverse applications such as power generation in fuel cells, natural gas engines and fuel for automobile systems.

The composition of carbon dioxide and other impurities in biogas depends on the composition of the substrate used. This will eventually increase the economic value of the gas. Currently, some biogas processing power plants are designed to remove carbon dioxide and other impurities. The three main processes of CO_2 removal are water wash, pressure swing adsorption (PSA) and chemical wash. In water wash, the properties of water are used for absorption and desorption of carbon dioxide. PSA uses pressurized and depressurized phenomena to absorb and release carbon dioxide. In chemical wash, an amine solution with stronger affinity for carbon dioxide removal is used. Two other emerging technologies are cryogenic and membrane separation. As the ambition for biogas refinement has to do with high technology, increased cost of production, technical removal of carbon-based and other impurities, it will be part of the future prospects for biogas utilization in Nigeria.

6.4. *Development of small-scale biogas power plants*

Development of small-scale bio-waste power plants is a common energy production approach for rural settlements. Energy supply structures especially in countries like India, Bangladesh and China with many rural settlements are usually handled on a small scale to minimize cost. In Nigeria, many rural communities are located such that they are sparse and geographically distributed in a way that access to modern social amenities is difficult. To satisfactorily overcome energy deficiency in such areas, especially in some niche rural communities, development of small-scale biogas-based power plants for distributed generation can be a viable option for electricity. This kind of energy development approach is particularly useful if the bioenergy feedstock used is found within the neighborhood of the power plant.

7. Discussions

Based on the evaluation so far, a total of 44.48 Gg of methane was generated from different livestock species under consideration in 2001. The value increased to 55.42 Gg (29.3 MW at 30% plant efficiency) in 2010, which is approximately a 20% rise over a decade. A steady increase in emissions has been observed between 2001 and 2002, with a slight decrease from 46.77 Gg in 2002 to 46.47 Gg in 2003 before bouncing back in continuous increments from 2004 to 2010. Evaluation of the methane emissions on individual livestock species analysis revealed that cattle generated the highest methane emissions, with chickens occupying the least position of emissions potential. Population statistics show that chickens have the highest head count among the livestock studied but produce the smallest quantity of manure and the lowest emission factor. Cattle and pigs have appreciable emission factors and produce a large quantity of physical manure. This contributes greatly to higher methane emissions despite these animals' limited number per head. As the trend observed so far is a continual increment in the emission level from the livestock, it is obvious that it will continue to induce more climate change as long as the methane is not presently being captured for energy or other applications.

Methane estimated from the generation of municipal solid waste from major capital cities and others is high enough to induce global warming effects. Estimated total methane productions in the geo-political regions are as follows: 90.64 Gg for the northeastern region, 175.56 Gg for the northwest, 99.00 Gg for the north-central, 59.40 Gg for the southeast, 241.56 Gg for the southwest, 132.44 Gg for the south–south and 114.84 Gg for the three selected cities in the country including the Federal Capital Territory (Abuja). The overall total is 913.44 Gg, equivalent to an electrical power potential of 482.4 MW at 30% plant efficiency. These values for each geo-political zone are expected to increase over time due to rapid growth in population of the country. A careful glance at the figures revealed that the southwestern region of the country maintains the highest value, followed by the northwest and then the south–south. The high values of methane emissions in the three regions can be attributed to their potential for commercial activities and concentration of human population. However, the southeastern zone also has strong potential because two out of three selected important cities in the country (Abakaliki and Onitsha) are from the zone. These two prominent cities are well identified for their commercial focus in the country.

8. Conclusion

This study has clearly pointed out the contribution of methane emissions from livestock and municipal solid waste generated in Nigeria. It is an indication that the country has a very strong potential for anaerobic digestion for biogas methane production to supplement energy consumption. Wide varieties of other biogas production resources from crop residues, waste water and sludge have not been discussed in this study, which means more opportunities for biogas methane production can be exploited in the country. The two primary benefits of capturing and optimizing this resource are to combat global warming and derive socio-economic gains. Finally, the study has unveiled a tremendous potential of one of the numerous RE resources in the country for future application. In the long-term, this will take the place of Kyoto benefits in sustainable development.

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